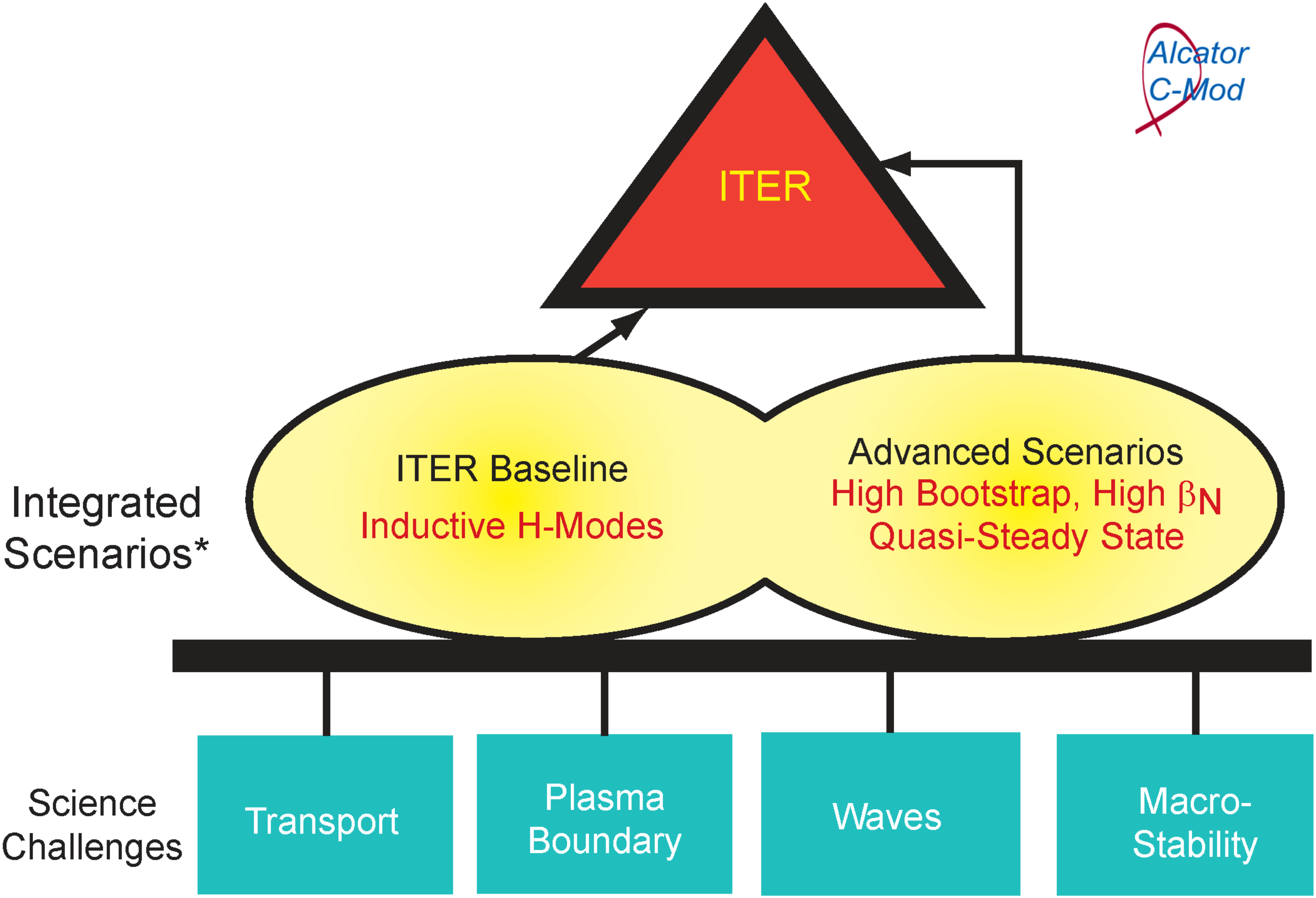
Alcator C-Mod
Highlights, Plans, Budget and Schedule
FY2006-FY2008

OFES Budget Planning Meeting

March 14, 2006

E. S. Marmar

for the Alcator Group

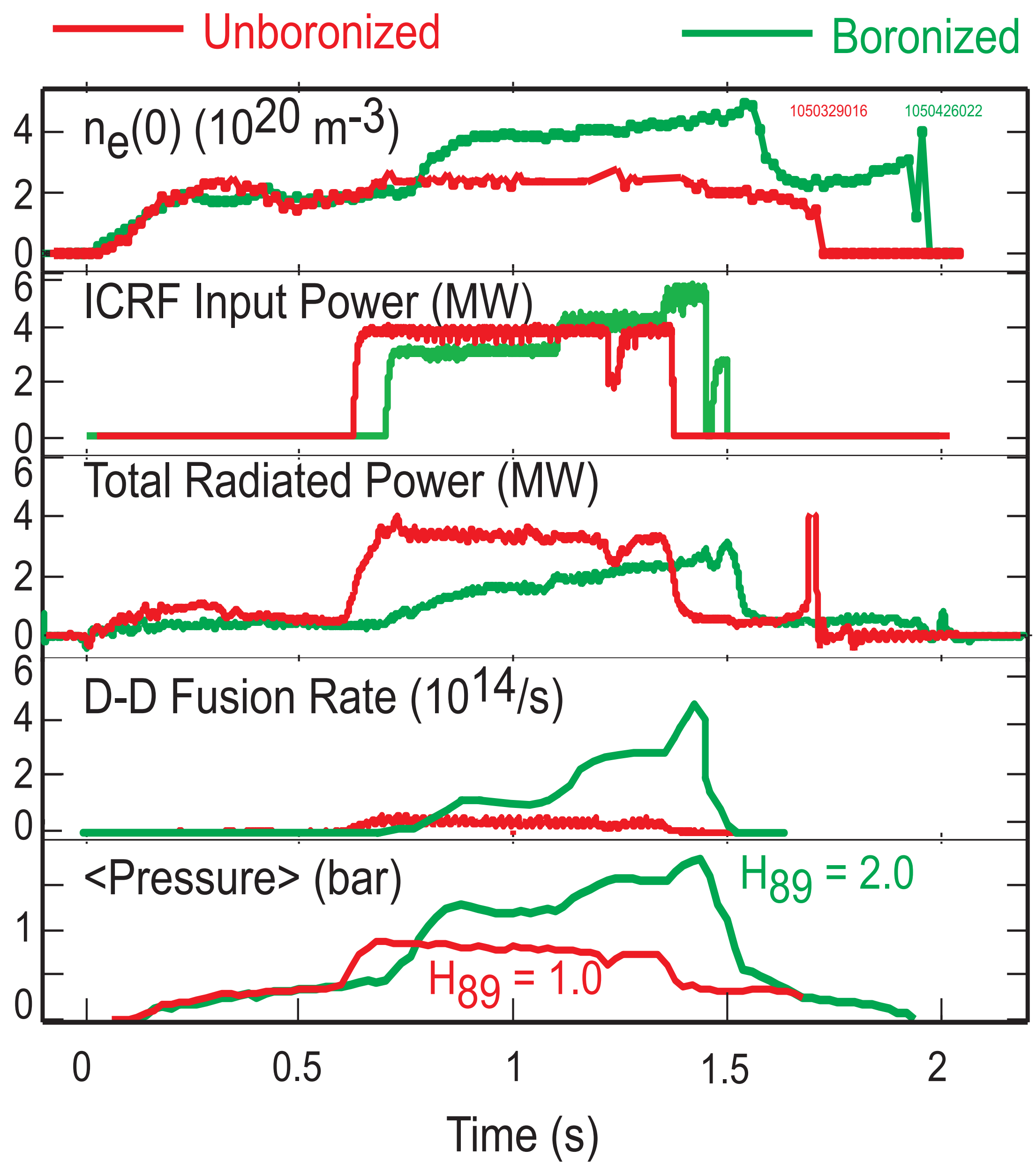


*Equilibrated electrons-ions, no core momentum/particle sources, RF I_p drive

Research Highlights 2005
All-Metal Plasma Facing Components

Alcator C-Mod

- Replaced all low-Z protection tiles (antennas)
- Removed boron build-up
- Extensive operation before first boronization
- Main results
  - Low z coating is required for high performance with high power ICRF
    - Mo radiation is main issue
  - Coatings last ~30 discharges (or 50 MJ RF input energy)
    - RF much more “efficient” than ohmic at removing boron
  - Localized areas appear to be critical

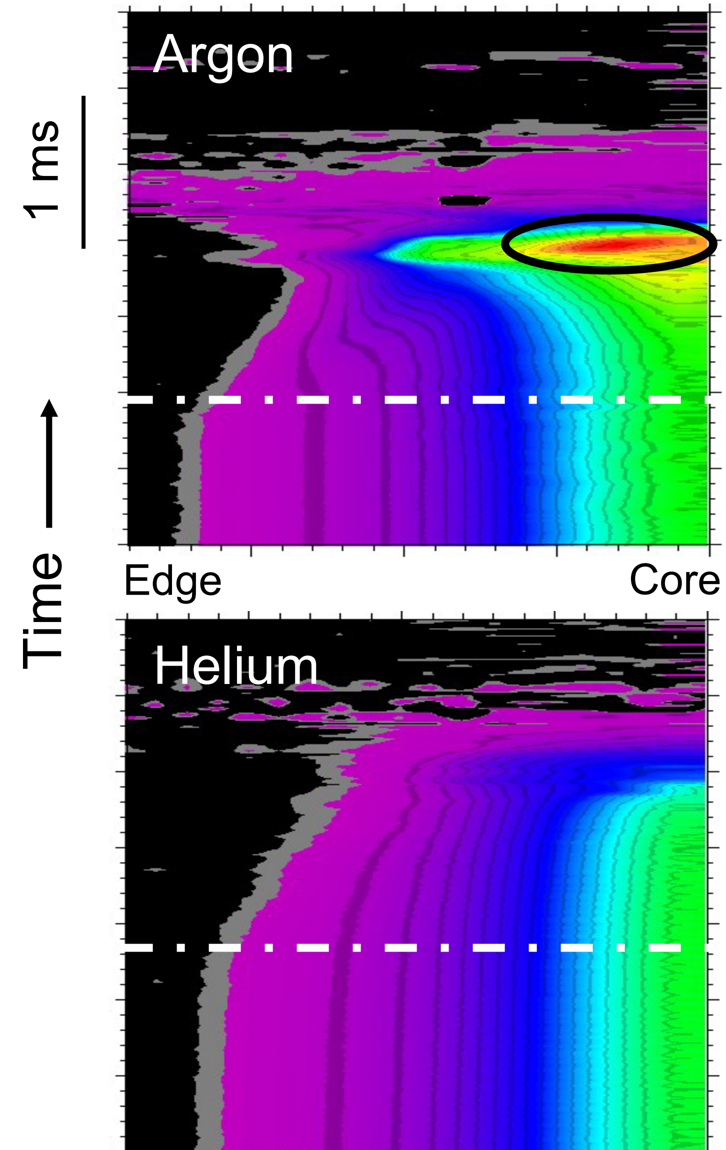


B. Lipschultz, et al., APS-DPP 2005 Invited, and PoP in press

Disruption Mitigation demonstrated with Massive Noble Gas Injection

- Higher pressure plasmas than previous experiments on other devices (~10x) (comparable to ITER)
- Halo current reduced ~50%
- More energy converted to (relatively) benign radiation
  - Close to 100% for higher Z gases
- Measurements show impurities do not penetrate to the core as neutrals
  - NIMROD modeling shows critical role of MHD

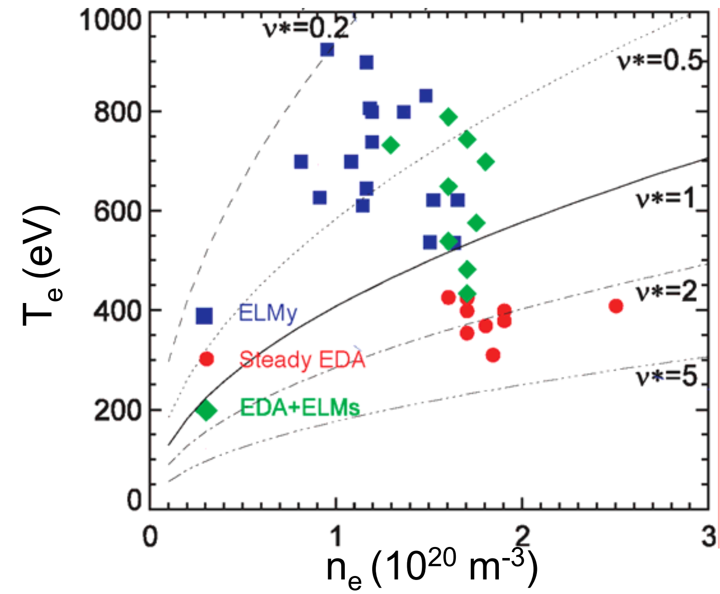
X-Ray Emissivity Contours:
Core emission enhanced with Ar, not He

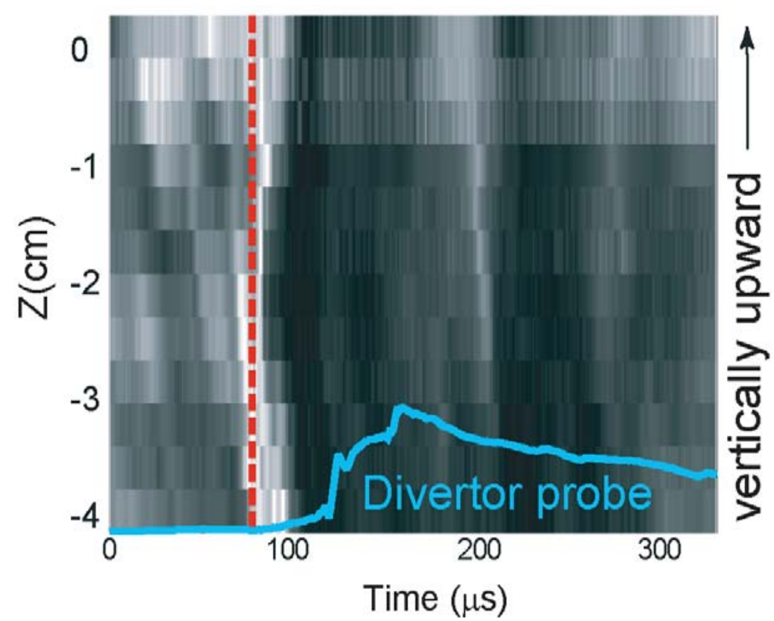


R. Granetz, et al., APS-DPP 2005 Invited

ELM regimes dependent on β, shape and collisionality

- Four regimes studied
  - ELM-free
  - EDA (quasi-coherent mode regulation)
  - EDA → ELMy
    - Small ELMs at higher β_N
  - Discrete ELMs
    - Lowest ν^*, high δ
    - High time resolution measurements show ballistic dynamics



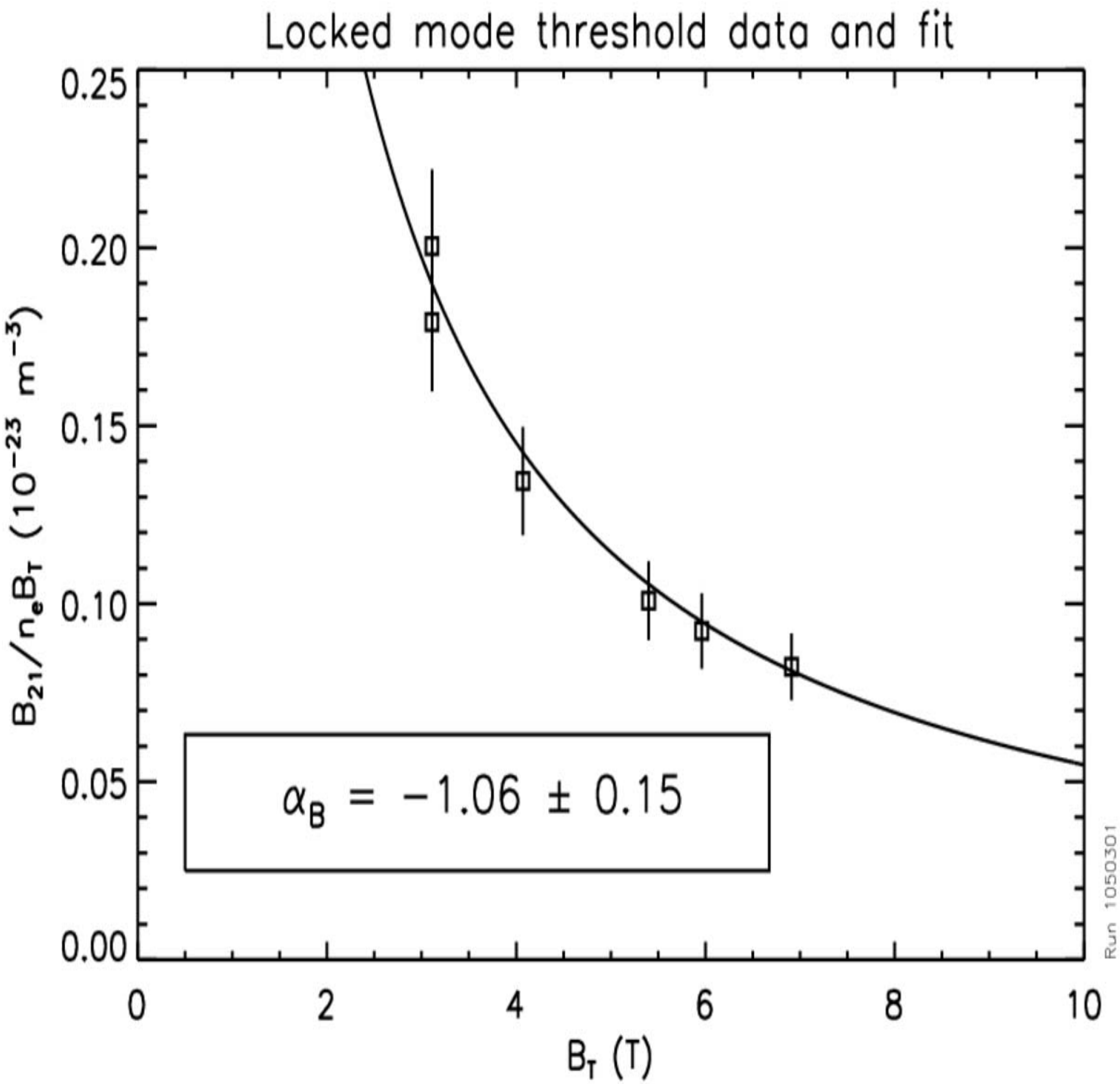


Discrete ELMs propagate ballistically outward near mid-plane; clear delay before reaching the divertor

J. Terry, et al., APS-DPP 2005

Error Field/Locked Mode Studies Constraining Extrapolation to ITER

- Extended studies over wide B range on C-Mod (spanning ITER B)
  - Fixed n/n_G and q (ITER values)
- Dimensionless constraints imply favorable scaling to ITER [$\propto R^{(.68 \pm .2)}$]
- Joint (ITPA) C-Mod-JET experiments
  - Fixed ρ^*, ν^*, q, β
  - gives $\alpha_B = -2.5 \pm .5$
    - Implies $R^{-(1.38 \pm .25)}$



Near-SOL ∇P Self-Organizes toward Critical $\nabla\beta_{pol}$ (α_{MHD})

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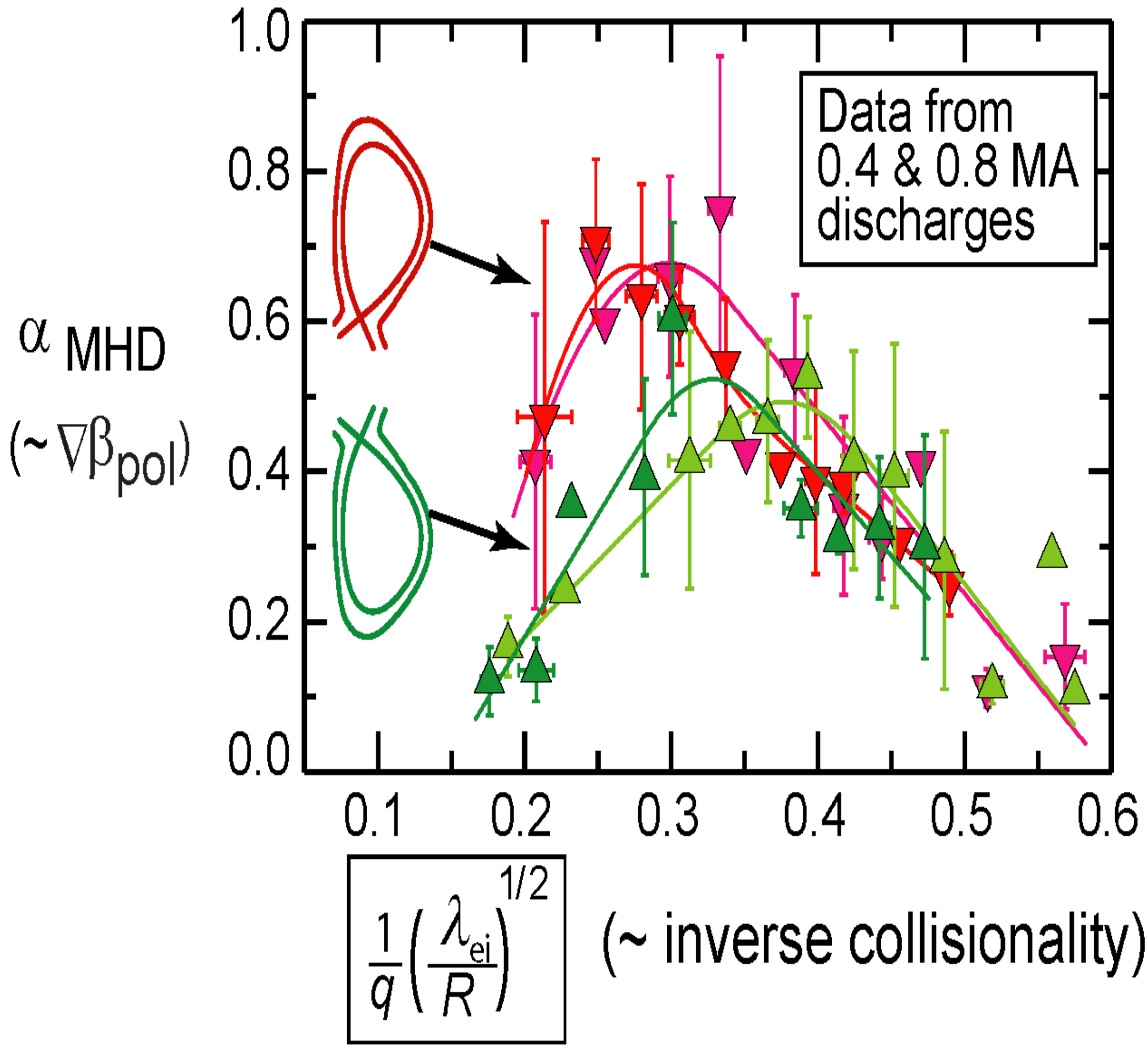
- Evidence that Electro-magnetic Fluid Drift Turbulence controls the edge†
  - Attainable α_{MHD} depends on collisionality
- New in 2005:
  - Depends on topology (LSN vs. USN)
  - ∇P near sep. $\propto I_P^2$
    - Higher α for LSN
- Suggests connection with edge flows and rotation
  - Contact with result of lower H-mode threshold for LSN



† B. LaBombard, et al., Nuclear Fusion **45**(2005)1658.

C-Mod plays a major role in education of the next generation of fusion scientists

- Typically have ~25-30 graduate students doing full-time Ph.D. research on C-Mod
  - Nuclear Science & Engineering, Physics and EECS (MIT)
  - Collaborators also have students utilizing the facility (U. Tx, U.C. Davis, U. Wisc., Politecnico di Torino)
  - Current total is 29
- MIT undergraduates participate through UROP program
- Host National Undergraduate Fusion Fellows during the summer

Budget Profiles (k$)

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Appropriation Guidance Base Full -10%

Institution	FY06	FY07A	FY08A	FY08B	FY08D
MIT	19,215	20,267	20,267	26,158	18,220
PPPL	1,993	2,047	2,047	2,747	1,860
U Texas	410	415	415	475	390
LANL	99	100	100	120	90
National Project Total (research run weeks)	21,717 (14)	22,829 (15)	22,829 (13)	29,500 (25)	20,560 (8)

*Reduction in Force: 1.5 Scientists, 2 Students, 2 Engineers, 1 Technician

Incremental Funds (~10%) Would Significantly Improve Progress

Alcator C-Mod

- Facility Operation: 6 additional run weeks
  - Only ~1/3 of priority runs can be accommodated in 14 weeks (FY06)
- Significantly earlier implementation of key upgrades
  - Tungsten tile outer divertor
    - ITER material and tile configuration
  - 4th MW Lower Hybrid Source Power
- Increased reliability, increased utilization
  - Real-time matching – final 3 ICRF transmitters
  - Spare LH Klystron

Collaborations are Significant in all Aspects of the Program

Domestic Institutions

Princeton Plasma Physics Lab
U. Texas FRC
U. Alaska
UC-Davis
UC-Los Angeles
UC-San Diego
CompX
Dartmouth U.
GA
LLNL
Lodestar
LANL
U. Maryland
MIT-PSFC Theory
ORNL
SNLA
U. Texas IFS
U. Wisconsin

International Institutions

Budker Institute, Novosibirsk
C.E.A. Cadarache
C.R.P.P. Lausanne
Culham Lab
ENEA/Frascati
IGI Padua
IPP Garching
IPP Greifswald
JET/EFDA
JT60-U, JFT2-M/JAEA
KFA Jülich
KFKI-RMKI Budapest
LHD/NIFS
Politecnico di Torino
Risø National Laboratory.
U. Toronto

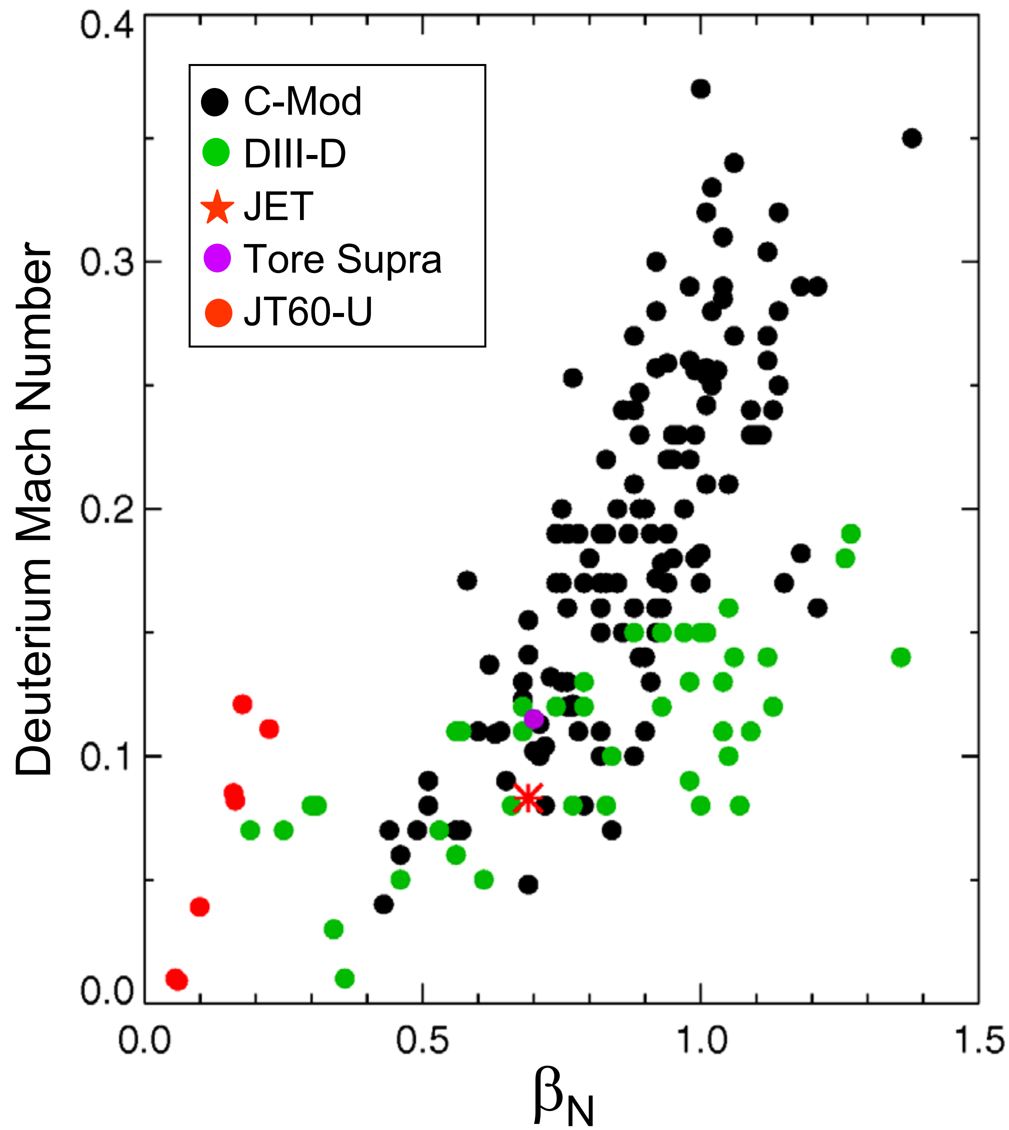
C-Mod Fusion Science and Technology Priorities

Understand matter in the high temperature state

Develop the science and technology to enable fusion energy

- Plasma Boundary
  - Turbulence and EDGE/SOL transport
  - Edge flows and coupling to core rotation
  - Hydrogenic isotope retention and recycling
  - High-Z PFC operational experience, including tungsten tile development
- Transport
  - Self-generated flows and momentum transport
  - Role of magnetic shear (enabled by LHCD)
  - Role of collisionality (enabled by cryopump)
  - Fluctuations and Electron transport
  - Particle and Impurity transport

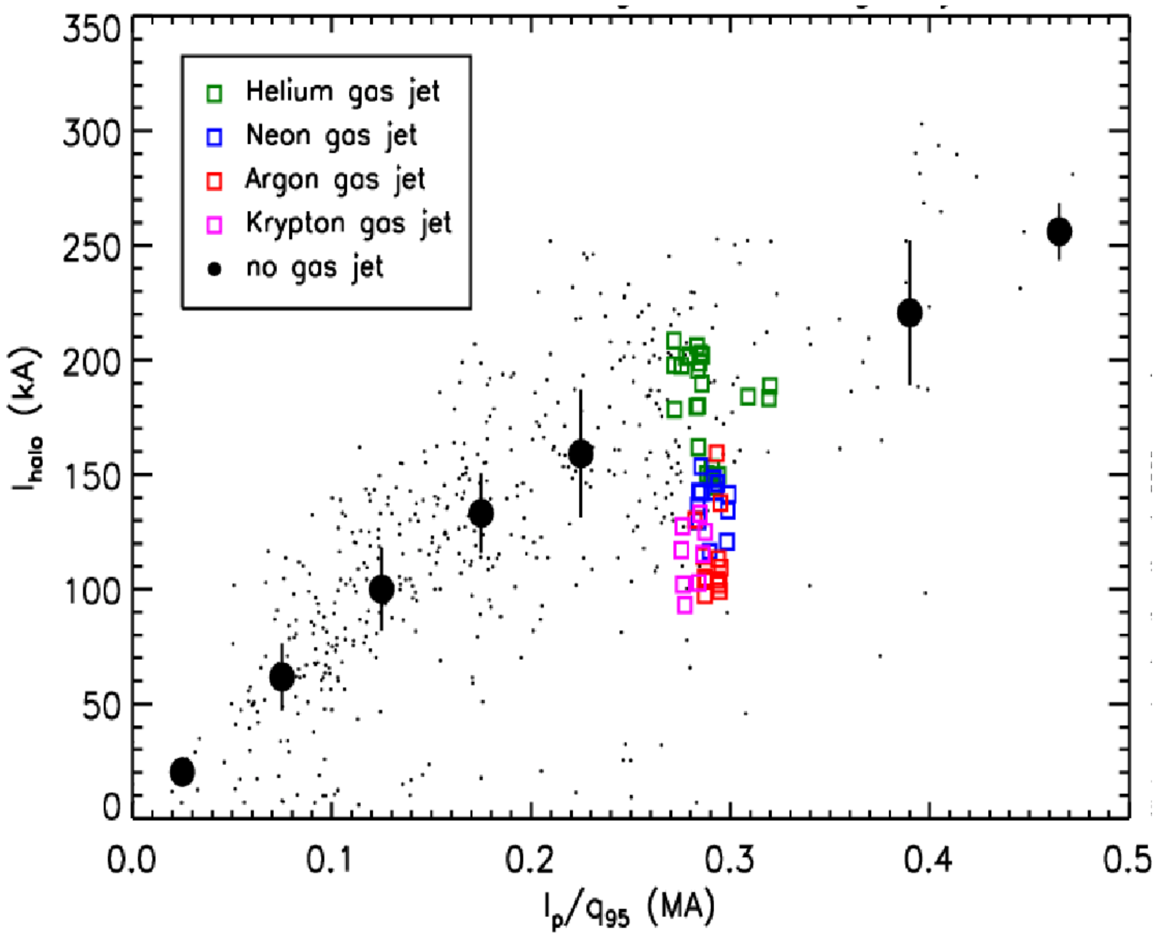
Inter-machine comparisons of spontaneous toroidal rotation beginning to bear fruit



C-Mod Fusion Science and Technology Priorities (cont'd)

- Macroscopic Stability
  - Disruption mitigation (massive gas puff); Disruption database (ITPA)
  - Locked modes (joint experiments)
  - Alfven modes, cascades
  - Sawtooth Stabilization
- Waves
  - Lower Hybrid
    - Coupling/Phase studies
    - Current drive, heating
  - Ion Cyclotron
    - Mode conversion current drive
    - Antenna-Plasma interactions
      - RF coupling
    - Minority ^{3}He heating

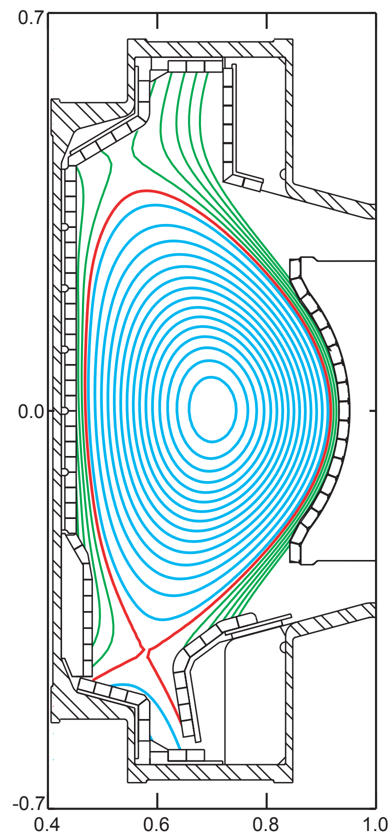
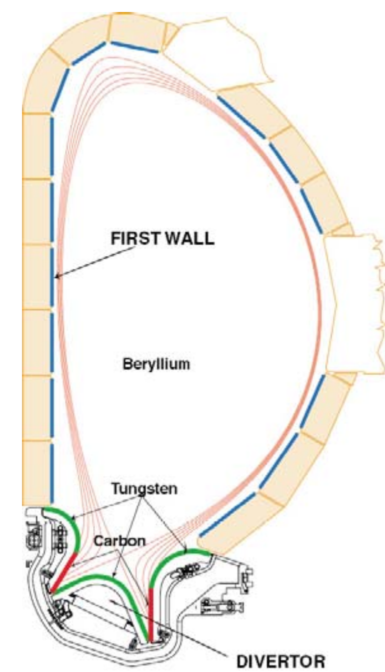
Higher Z gases better at reducing halo currents during mitigated disruptions



C-Mod well positioned to help solve challenges for ITER

Create a star on earth

- Unique regimes
  - ITER B field, density, power density, plasma pressure
    - Disruption mitigation
    - Neutral opacity, Radiation Transport
  - High leverage database contributions
    - Dimensionally unique
    - Non-dimensional match to larger, lower field tokamaks
- ITER heating and current drive tools
  - Lower Hybrid Off-Axis CD
  - ICRF minority heating, MCCD
  - Torque and particle source free
    - Transport-driven rotation
- All-metal high-Z Plasma Facing Components
  - Molybdenum → Tungsten
    - Tritium retention, Impurity dynamics, Detachment
  - Low-Z wall coatings

C-Mod	ITER/9
	
B_T = 5.3T, I_p = 1.6MA	**B_T = 5.3T, I_p = 15MA**
B ≤ 8.1 T, I ≤ 2.0 MA	
$\beta_N \le 1.8$, $Z_{eff} \sim 1.5$	$\beta_N = 1.75$, $Z_{eff} < 1.6$
$0.1\times10^{20} < n_e < 10\times10^{20}$	$n_e = 1\times10^{20}\ m^{-3}$
$P_{\parallel}(SOL) \le 0.5\ GW/m^2$	$P_{\parallel}(SOL) \approx 1\ GW/m^2$

Research strongly motivated by, aligned with, high priority ITPA/ITER research tasks

Alcator C-Mod

- Boundary Science
  - SOL plasma interaction with main chamber
  - H isotope (tritium) retention, removal
  - Inter-ELM transport, $\perp$ SOL transport
  - Dimensionless cross machine comparisons for SOL physics
- Pedestal
  - Small ELM regimes
  - Structure: transport and atomic physics
  - Contributions to pedestal database
- Transport physics
  - Reactor relevant conditions (electron heating, equilibrated e-i, low momentum input)
  - Commonality of transport physics in hybrid, s.s. scenarios with reactor relevant conditions
  - Comparisons of turbulence measurements with simulations
- Macrostability
  - Disruption mitigation and disruption database
  - Intermediate-n Alfven Eigenmodes (active antennas)
  - NTM stabilization, Sawtooth stabilization
- Confinement database and modeling
  - Effects of ν^* vs n/n_G, β scaling, ρ^* scaling, analysis of ITER reference scenarios
  - Density peaking
- Steady State Operation
  - Real-time control of advanced scenarios
- Diagnostics
  - Dust measurement, erosion

Strong Participation in Joint Experiments Coordinated through ITPA

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- CDB-4 Confinement scaling in ELMy H-Modes: ν^* scaling at fixed n/n_G
- CDB-8 ρ^* scaling along ITER relevant path
- CDB-9 Density profiles at low collisionality
- TP-4.1 Similarity experiments with off-axis ICRF and density peaking
- TP-6.1 Scaling of spontaneous rotation with no external momentum input
- TP-8.2 Investigation of rational q effects on ITB formation and expansion
- PEP-7 Pedestal width analysis by dimensionless edge identity experiments
- PEP-10 Radial efflux at the mid-plane and ELM structure
- PEP-16 C-Mod/NSTX/MAST small ELM regime comparison
- PEP-17 Small ELM regimes at low pedestal collisionality
- DSOL-3 Scaling of radial SOL transport
- DSOL-4 Comparison of disruption energy balance and heat flux profile
- DSOL-5 Role of Lyman absorption in the divertor
- DSOL-11 Disruption mitigation experiments
- DSOL-13 Deuterium codeposition in gaps of plasma facing components
- DSOL-15 Inter-machine comparison of blob characteristics
- MDC-1 Disruption mitigation by massive gas jet
- MDC-5 Comparison of sawtooth control methods for NTM supression
- MDC-6 Low β error field experiments
- MDC-10 Damping rates of intermediate n Alfven Eigenmodes
- SSO-2.3 ρ^* dependence on confinement, transport and stability in hybrid scenarios

C-Mod **Leading** or Strongly Contributing to CY2006 US Science Tasks for ITER

1. RWM Control
2. **Disruption Mitigation**
   - **Dennis Whyte (Participant Team Leader), Bob Granetz (co-PI)**
3. Fast Particle Confinement
   - Joe Snipes (C-Mod data and NOVA-K simulations)
4. **Effects of Radiation Transfer on Divertor Plasma**
   - **Bruce Lipschultz (P.T. Leader), Steve Lisgo (co-PI), Jim Terry (C-Mod data)**
5. ICRF Heating and Current Drive – Benchmarking of ICRF Codes
   - Paul Bonoli (co-PI), Steve Wukitch (C-Mod data)

C-Mod Contributions to Priority ITER Science

- Integrated Scenarios
  - Lower Hybrid Current Drive for Advanced Tokamak scenarios
    - Hybrid scenarios
    - Quasi-steady-state, fully non-inductive
  - Compatibility of high-Z Plasma Facing Components
  - H-Mode pedestal physics
  - Small ELM regimes
  - H-Mode threshold physics

C-Mod Contributions to Priority ITER Science

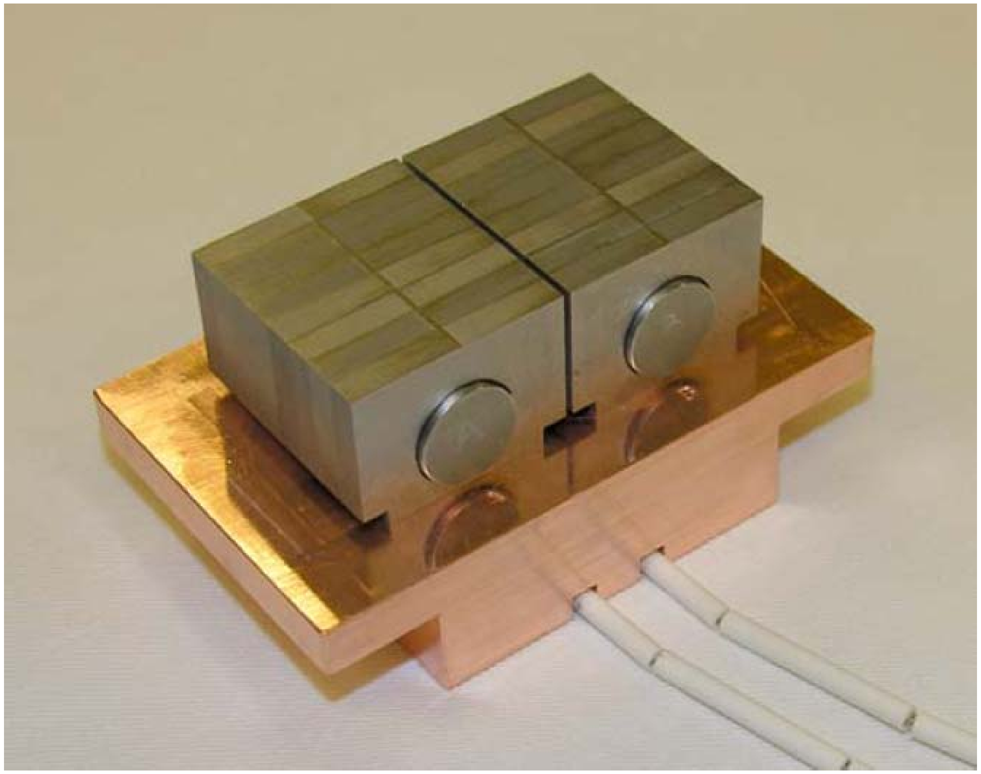
Alcator C-Mod

- Boundary
  - Erosion, Deposition
  - Tritium retention and removal
  - Radiation transfer in the divertor and effects on detachment
  - Divertor viscosity, atomic and molecular collisions (high neutral density)
  - Cross-field SOL transport, filamentary turbulence
- Macrostability
  - Disruption mitigation (including MHD and radiation physics)
  - Error field/locked mode physics
  - Intermediate toroidal mode number Alfven Eigenmodes
- Transport
  - Torque-free rotation, momentum transport
  - Density peaking, particle transport, impurity transport
- Wave-Plasma
  - Fast wave minority heating (including low single-pass absorption regimes)
  - Mode-conversion heating and current drive
  - ICRF code benchmarking
  - ICRF coupling (experiment and modeling)
  - Lower Hybrid: propagation, absorption and far off-axis current drive
  - Sawtooth stabilization

C-Mod Contributions to Priority ITER Technology

Alcator C-Mod

- Disruption mitigation (massive gas)
- Tungsten Plasma Facing Components
- Real-time ICRF matching
- Data system tools
- Remote participation tools
- Wall conditioning/coating (including during-shot)
- Dust detection

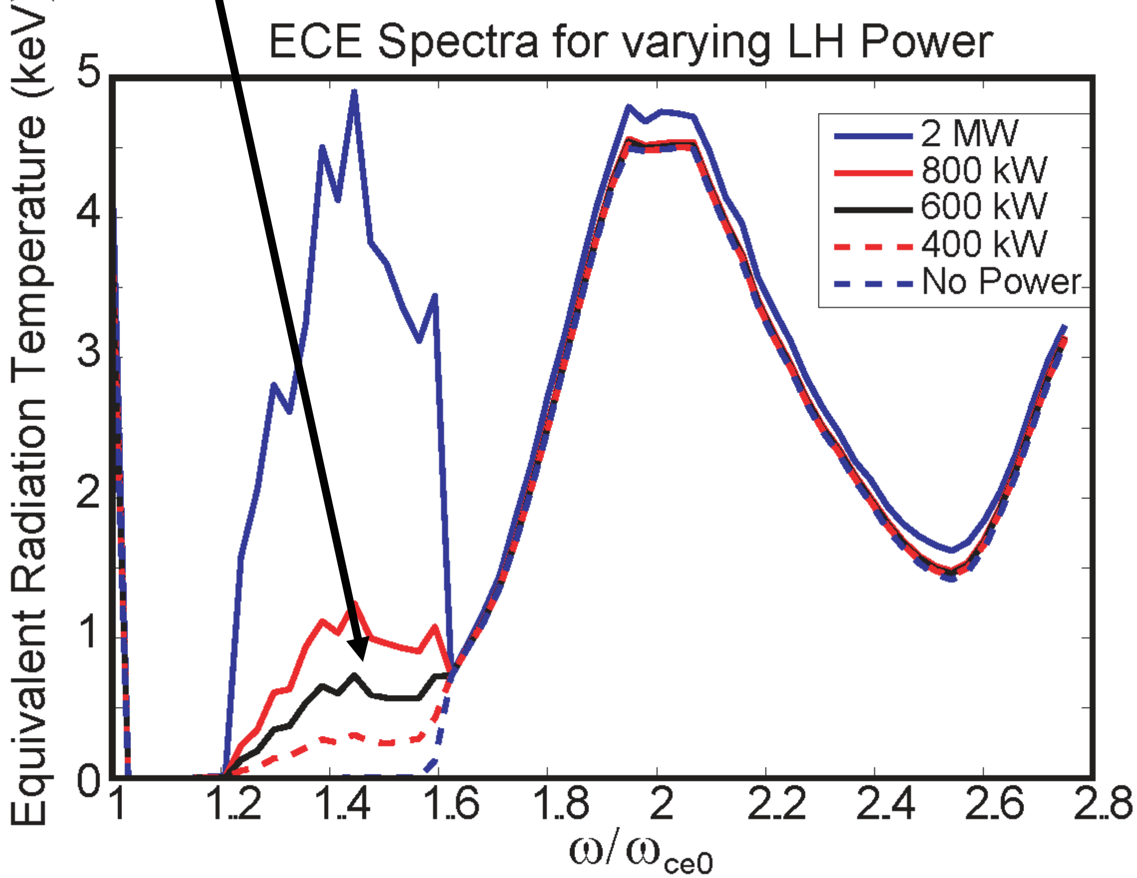


- ITER style laminar plate tungsten tiles being tested for power handling (Sandia and Jülich)
- Installation and testing in C-Mod (FY06-07)

AT Operation likely needed for Successful ITER Quasi-Steady-State

- C-Mod has entered key new phase of AT program: demonstrate RF tools for current profile control
  - LHCD system commissioned
  - Current drive experiments beginning
    - About 0.5 MW coupled to plasma in first week of FY06 LH operations
- Good progress in understanding and optimizing core transport barriers with localized ICRF
  - Higher power, central n and T
  - As j(r) control becomes available, explore influence of shear on transport and barriers
- Move toward integration of tools to produce high bootstrap fraction, non-inductive, long-pulse
  - Modeling, incorporating latest wave-plasma and transport understanding is key

Modeling predicted Significant LH driven tail electron population with 0.5 MW



Andrea Schmidt – APS 2005

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Alcator C-Mod

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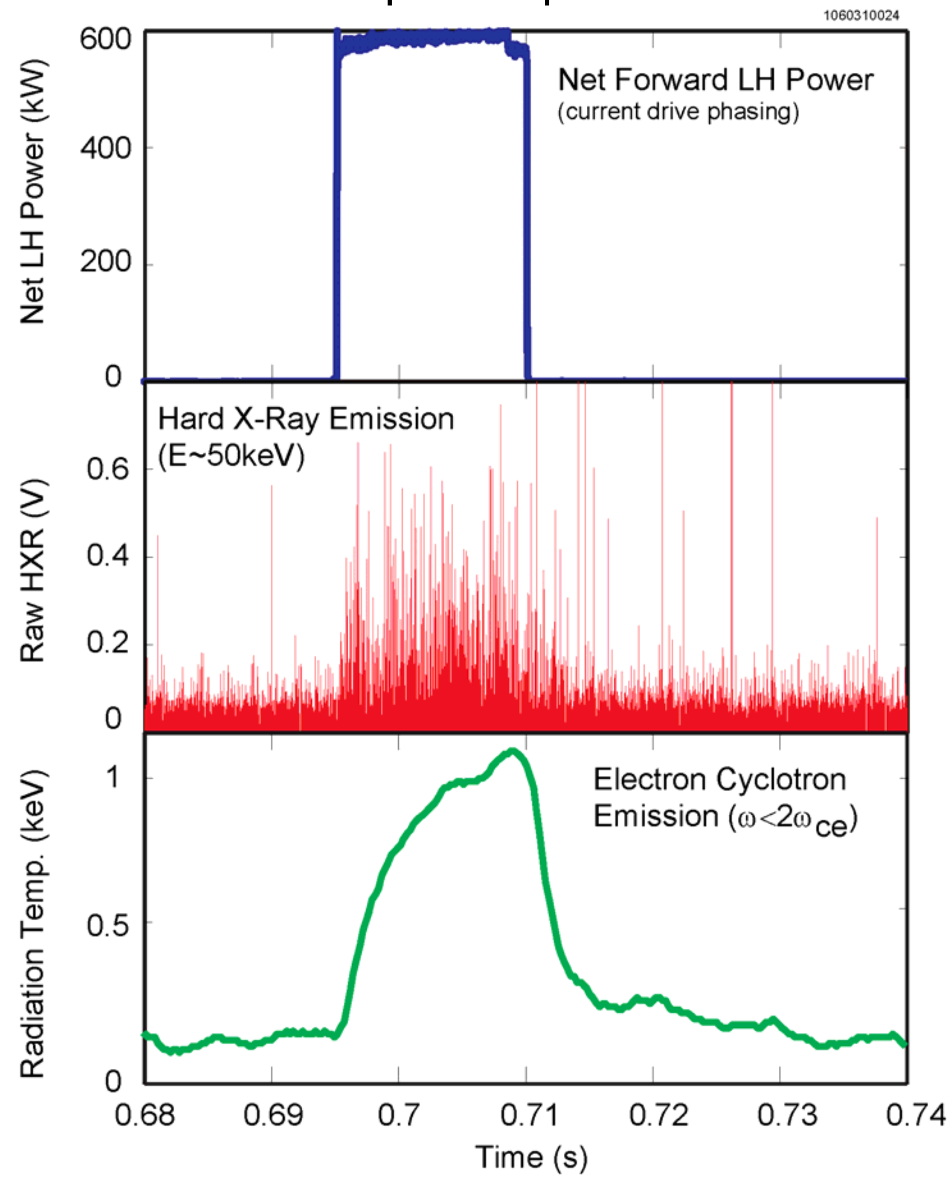
Clear signatures of LH driven electrons seen at expected power levels



C-Mod **Well Aligned** with US Fusion Science Priorities

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FESAC Priorities Panel Questions:

T1. How does magnetic field structure impact fusion plasma confinement?
T2. What limits the maximum pressure that can be achieved in laboratory plasmas?
T3. How can external control and plasma self-organization be used to improve fusion performance?
T4. How does turbulence cause heat, particles, and momentum to escape from plasmas?
T5. How are electromagnetic fields and mass flows generated in plasmas?
T6. How do magnetic fields in plasmas reconnect and dissipate their energy?
T7. How can high energy density plasmas be assembled and ignited in the laboratory?
T8. How do hydrodynamic instabilities affect implosions to high energy density?
T9. How can heavy ion beams be compressed to the high intensities required to create high energy density matter and fusion conditions?
T10. How can a 100-million-degree-C burning plasma be interfaced to its room temperature surroundings?
T11. How do electromagnetic waves interact with plasma?
T12. How do high-energy particles interact with plasma?
T13. How does the challenging fusion environment affect plasma chamber systems?
T14. What are the operating limits for materials in the harsh fusion environment?
T15. How can systems be engineered to heat, fuel, pump, and confine steady-state or repetitively-pulsed burning plasma?

C-Mod **Contributes Strongly** to 5 of 6 Identified Areas of “Opportunities for Enhanced Progress”

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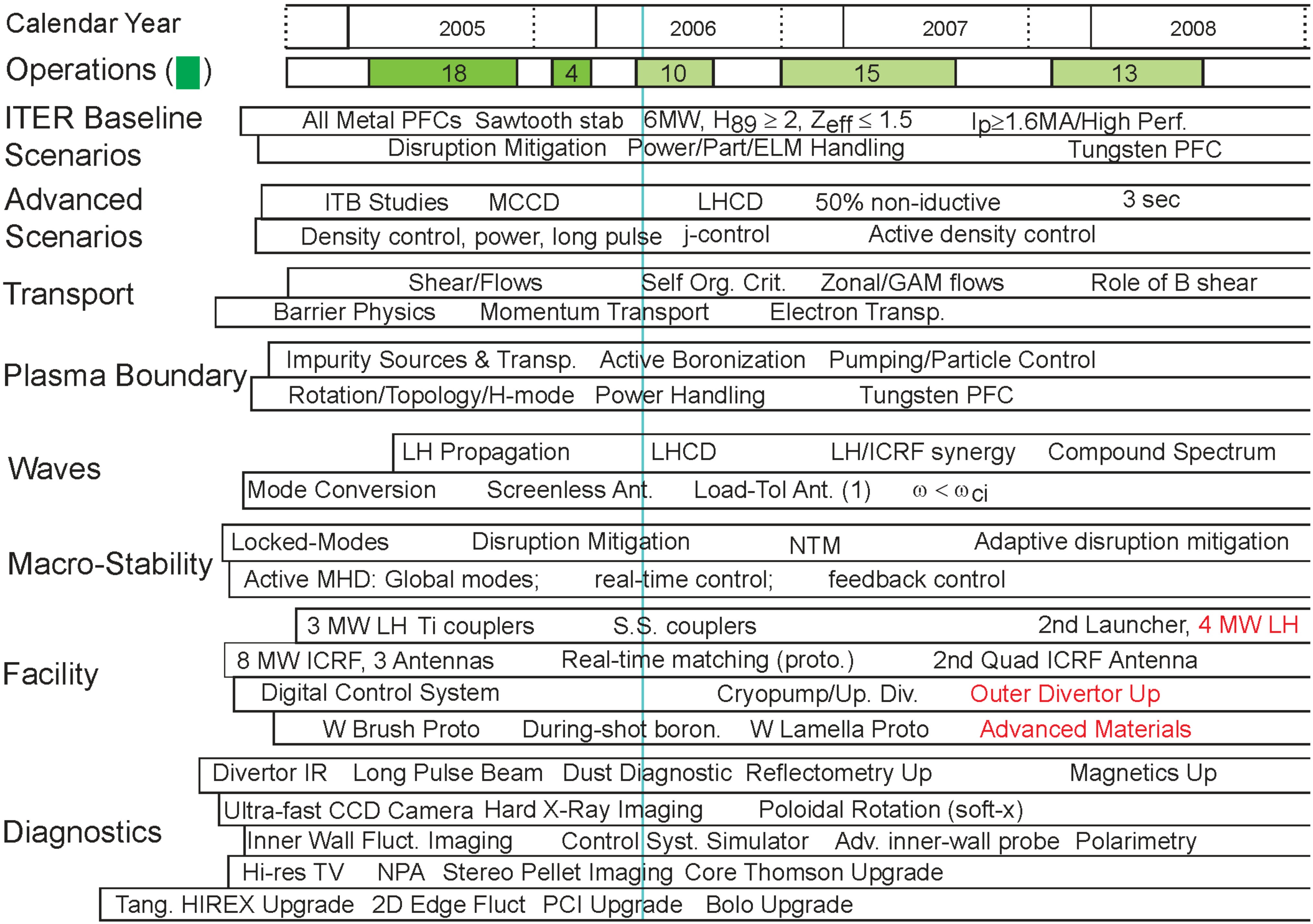
- Top 6 priorities for incremental resources:
  - **Support ITER construction and operation, including diagnostic R&D.**
  - **Predict the formation, structure, and transient evolution of the H-mode edge pedestal with high confidence.**
  - **Support the TTF initiative with emphasis on extended understanding of electron-scale transport.**
  - **Develop an integrated understanding of plasma self-organization and external control, enabling high-pressure sustained plasmas.**
  - Understand electron transport and laser-plasma interactions for Fast-Ignition high-energy density plasmas.
  - **Extend understanding and capability to control and manipulate plasmas with external waves.**

Alcator C-Mod
Overview Schedule (March 2006)

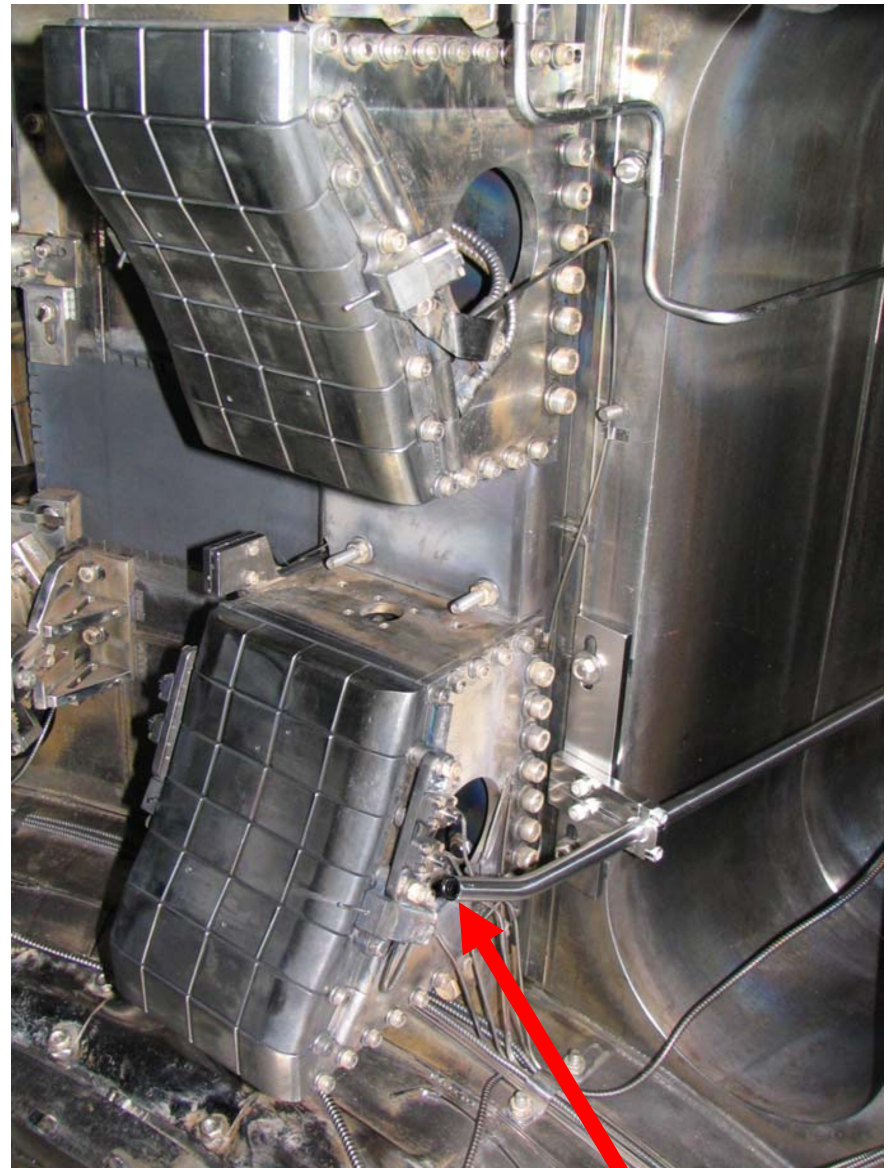


Research Goals (FY06-FY08)

Disruption mitigation of high pressure plasma	FY 2006
Sustaining plasma current without a transformer (50% non-inductive)	FY 2007
Current profile control with microwaves	FY 2007
Active density control	FY 2007
Confinement at high plasma current	FY 2008
Active control of ICRF antenna	FY 2008

Targets and Milestones

- Disruption mitigation of high absolute pressure plasma (FY06)
  - Successful experiments and modeling well underway
- Non-inductive sustainment of plasma current (FY07)
  - Intermediate goal: 50% non-inductive
- Current profile control with microwaves (FY06-07)
  - Far off-axis current drive



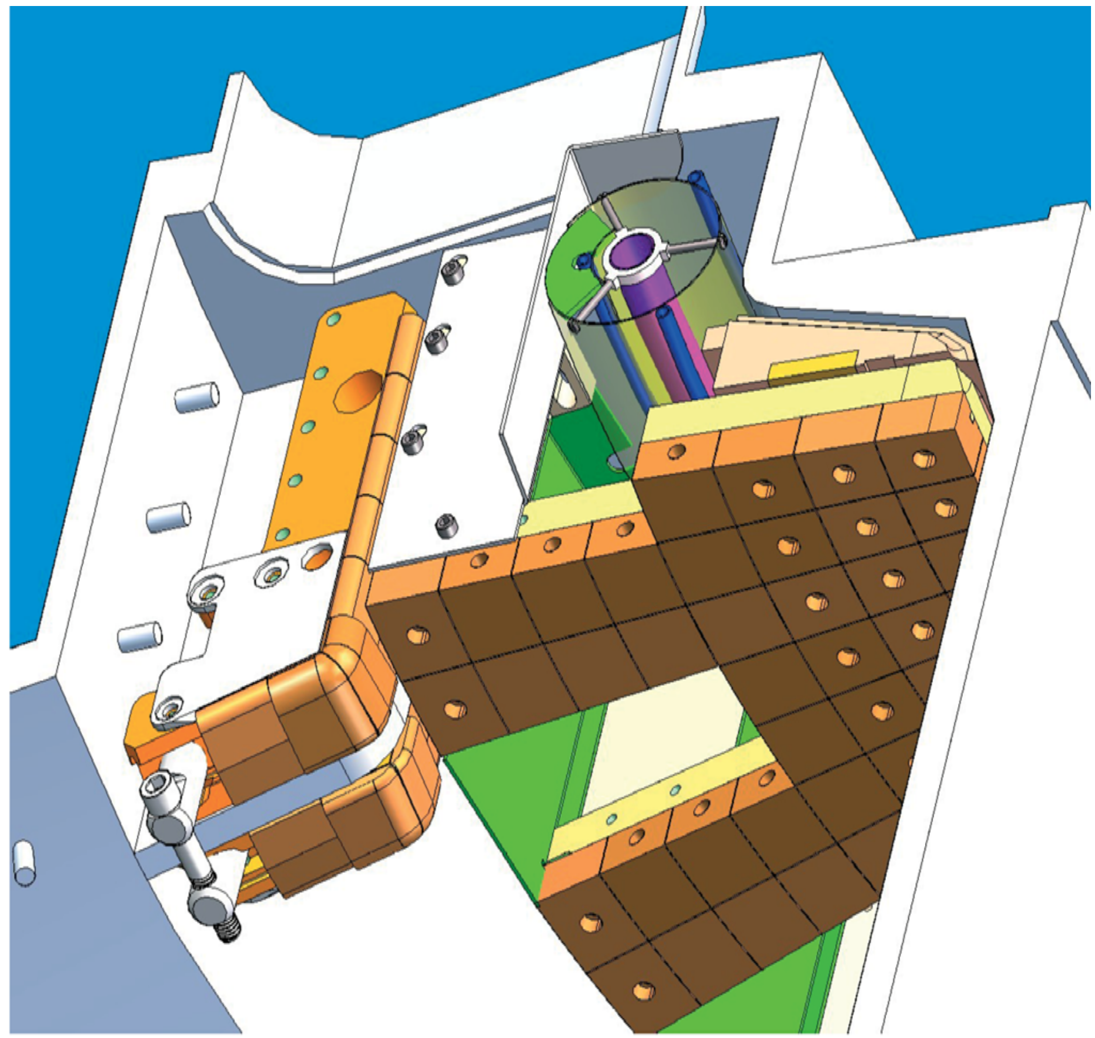
Disruption mitigation gas tube (outlet 2 cm from LCFS)

Targets and Milestones (cont'd)

- Active Density Control (FY07)
  - Install divertor cryopump (summer 2006)
  - Low density H-modes for AT regimes with efficient LH current-drive
- Confinement at high plasma current (FY06-08)
  - $I_p \geq 1.5$ MA
- Active control of ICRF antenna (FY07-08)
  - Maintain coupling across L/H transitions and ELMs

Upper Divertor Cyropump

Construction Nearing Completion



Incremental Funds for C-Mod in FY07-08 would Enable Significantly Extended Scientific Progress*

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Transport Science	Momentum transport in torque-free discharges	Electron thermal transport	Compare near marginal stability fluctuations with non-linear GK models	Role of equilibrium and fluctuating flows in L/H threshold	Nature of momentum coupling at edge
Plasma Boundary	SOL turbulence and transport	ITER prototype tungsten divertor module studies	High-Z first wall studies		
Wave-Plasma	Lower Hybrid j-profile control	Real-time ICRF matching	ICRF/LHCD synergies	LHCD with compound spectrum (2 launchers)	
Macro-Stability	Adaptive disruption mitigation	NTM Threshold at increased β	Fast-particle-driven collective modes in low/reversed shear	Test feedback stabilization of NTMs	
Conventional H-Modes	H-mode pedestal scaling	Confinement at high I_p	Exploit sustained high reactivity scenarios	Characterize and exploit small ELM regimes	High power handling of tungsten divertor
Advanced Scenarios	Active density control	50% non-inductive scenarios	Optimize hybrid scenarios with equilibrated electrons/ions	Generation and control of ITBs via manipulation of B shear	Fully non-inductive, quasi-steady-state

*Progress expected in most topics (red indicates incremental funds required for hardware upgrades and/or increased run time)

Summary National Budgets, Run-time and Staffing

	FY05 Actual	FY06 Approp.	FY07A Request	FY08D Reduced	FY08A Level	FY08B Full
Funding ($ Thousands)						
Research		8,510	8,890	8,110	8,890	11,280
Facility Operations		13,207	13,939	12,450	13,939	18,220
Research Capital Equipment		293	302	250	302	360
Operations Capital Equipment		99	100	90	100	120
PPPL Collaborations		1,993	2,047	1,860	2,047	2,747
UTx Collaborations		410	415	390	415	475
LANL Collaborations		99	100	90	100	120
MDSplus		147	151	140	151	200
International Activities		75	80	60	80	100
Total (inc. International)		21,792	22,909	20,620	22,909	29,600
Staff Levels (FTEs)						
Scientists & Engineers		55.2	54.8	49.4	53.9	65.5
Technicians		25.5	25.6	24.3	25.6	30.3
Admin/Support/Clerical/OH		12.2	12.6	11.9	13.4	14.6
Professors		0.2	0.2	0.2	0.2	0.2
Postdocs		2.0	2.0	0.0	2.0	3.0
Graduate Students		29.0	28.0	26.0	28.0	31.0
Industrial Subcontractors		1.4	1.2	1.0	1.0	1.4
Total		125.5	124.4	112.8	124.1	146.0
Facility Run Schedule						
Scheduled Research Run Weeks	17 (18.4)	14	15	8	13	25
Users (Annual)						
Host	38	39	39	35	38	52
Non-host (US)	63	65	66	59	63	93
Non-host (foreign)	46	48	48	40	45	55
Graduate students	29	29	29	26	29	31
Undergraduate students	5	7	7	4	6	10
Total Users	181	188	189	164	181	241
Operations Staff (Annual)						
Host	70	67	68	63	67	76
Non-host	4	4	4	3	4	5
Total	74	71	72	66	71	81

C-Mod is Major Contributor to Fusion Science and Preparations for ITER Burning Plasma

- Unique dimensional regimes
- ITER relevant heating and current drive tools, metal PFCs
- Increasingly strong collaborations
- Strong, broad contributions to high priority ITPA/ITER research
- Tight coupling to theory and modeling
- Exciting prospects in coming 3 years with new tools and diagnostics
  - LHCD; cryopump
  - Disruption mitigation
  - Turbulence measurements
  - CNPA, Hard X, long-pulse DNB
  - Polarimeter [(j(r)]
  - All digital plasma control system